Numerical Simulation of Electro hydrodynamic pump using COMSOL

Rahul Sahu[1], Anjana[1], Rachana Nareti[1], Swastika Patel[1*], Neha Singh[1], Sanjana Mandavi[1]

[1]Department of Mechanical Engineering, Government Engineering College Raipur 492015

ABSTRACT

Electrohydrodynamic (EHD) pumps, also referred to as fluid dynamic pumps (FDPs), utilize electric fields to propel fluids without conventional mechanical parts. They find applications in microfluidics, cooling systems, and aerospace due to their simplicity and low maintenance, although they may have limitations in efficiency and flow rates. The EHD pump effect directly transforms electrical energy into kinetic energy. Recently, EHD pumps, which utilize this effect to transport functional fluids and gases, have garnered significant interest in Electro-hydrodynamic phenomena entailing the interaction between electric fields and flow fields within a dielectric fluid medium our analysis of an EHD pump using COMSOL software has yielded valuable insights into its plug flow and velocity gradient.

Introduction: -

The electrohydrodynamic (EHD) process is a fluid dynamic technique that utilizes electric fields to manipulate fluids. Electrodes are employed to generate electric fields within the fluid, enabling control over fluid movement and behavior. The EHD effect directly converts electrical energy into kinetic energy. It is a versatile process with various applications and typically consists of electrodes and a dielectric fluid. EHD pumps are typically small in size, often in the microscale, with pipe sizes typically around 1/8 inch (3.175 millimeters) or even smaller. They are used in small irrigation systems and scientific instruments.

When a high voltage is applied to the electrodes, an electric field is created, which interacts with the fluid and induces motion. Since EHD pumps do not have mechanical parts, there is no friction, heat generation, or need for lubrication. Maintenance is low, and they are used in specific applications. However, despite the rapid growth of this field, there are few comprehensive reviews of recent literature on soft EHD pumps.

Keywords: - Electro Hydrodynamic (EHD) Pump, ionic pump, charge transport,

Nomenclature: -

- ρ_e: Charge density
- V: Electric potential
- E: Electric field
- $\in$: Electrical permittivity
- σ: Electrical conductivity
- ρ: Fluid density
- $\overline{u}$: Fluid velocity field
- μ: Dynamic viscosity
- P: Fluid pressure
- e_0: Elementary charge
- D: Diffusion coefficient
- R: Reaction rate
- T: Absolute temperature and
- n_e, p_e: Charge concentration

Brief History of EHD Pump: -

In 1961, Robison proposed the idea of an electrostatic blower known as the EHD gas pump, which had advantages over conventional fans like low wear and quiet operation. However, its low efficiency disappointed Robison, leading to various research efforts to improve it. Morrow et al. made significant progress in 2008 by achieving an electrical energy conversion efficiency of 1.72%. June et al. further demonstrated higher efficiency, reaching up to 14% with a mesh-like EHD pump. In addition to air pumps, EHD pumps for functional fluids have been developed. Crowley et al. Conducted pioneering

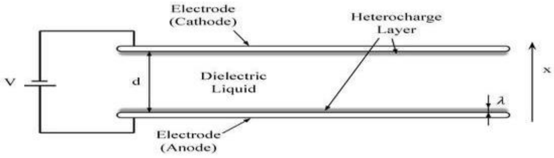

Fig.1 Fluid EHD pump Geometry [1]

Figure 1: EHD pump geometry. Here, L, d, and w represent the channel length, depth, and width, respectively. V denotes the high voltage power source [1].

Plug charge: - The term “plug charge” typically refers to a type of electrical charge distribution within a dielectric medium, often encountered in the context of electrohydrodynamic (EHD) phenomena or in the study of electrical breakdown in insulating materials. In the context of EHD, plug charge refers to the accumulation of electric charge, typically in the form of ions, within a confined region of the.

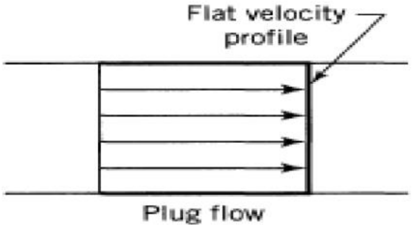

Fig.2 Plug flow [2]

Literature review: -

Electrohydrodynamic pumping of” Dielectric Liquids” by A.A. GOLOVIN and V.P. Shevchenko [2]. This paper provides a comprehensive overview of EHD pumping, including the basic principles, different types of EHD pumps, and applications. Theory and Applications” by M.K. CHUDHARY and M.M. RAMAN [3]. This book provides a more in- depth treatment of EHD flows, including the mathematical modeling and numerical simulation of EHD pumps. Principles and Applications’ by J.R. Melcher [4]. This book is a classic text on EHD, covering the fundamentals of EHD as well as a variety of applications. Electro hydrodynamic Actuators and Flow control” by J.H. Kim and J.Y. Park [5]. This book covers the use of EHD Force at actuators and to control the flow of fluids. One study by smith et al. [6] investigated the performance of different electrodes configuration in EHD pumps and their impact on fluid flow. They concluded that the electrode Geometry significantly affects the pumping efficiency and flow characteristics. Johnson and Brown [7] focused on the optimization of EHD pumps for cooling applications. They explored various factors such as voltage, frequency, and electrode spacing to enhance the heat transfer capabilities of the pump, their findings suggested that higher voltages and lower frequencies can improve the cooling Performance. A review article by Chen et al. [7] provided and overview of the recent advancements in EGD pump, including those based on corona discharge and field induced ion injection. The review highlighted the potential of EHD pumps in fields such as microfluidics, drug delivery, and cooling Systems.

Methodology: -

Governing equations: - This paper investigates the foundational aspects and numerical simulation of Electro hydrodynamic (EHD) pumps, focusing on their structural components and computational modeling using COMSOL Multi physics version 6.1. The EHD pump comprises twin electrode immersed in a dielectric, and electrostatic forces. Particle movement in non-uniform electric fields necessitates specifying permittivity, conductivities, fluid dynamics, electric currents, and particle mechanics. The numerical model, implemented with three physics interfaces, simulates EHD conduction phenomena, including laminar fluid flow, charge species transport, and electrostatics. The transient solution establishes initial conditions, followed by computational of steady- state solution, incorporating momentum conservation through the Stokes equation.

$$\nabla . \bar{u} = 0 \tag{1}$$

$$\vec{u}.\nabla\vec{u} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2\vec{\mu} + \frac{1}{\rho}\overrightarrow{F} \tag{2}$$

The fluid velocity field, ρ represents the fluid density, p denotes the fluid pressure, and μ stands for the fluid viscosity. The fluid is considered to be laminar and incompressible. The energy equation is not included due to the assumption that joule heating is negligible.

The thermodynamic body force $\bar{F}$ only considers the Coulomb force and is expressed through charge concentration.

$$\vec{F} = (p_e - n_e)\vec{E} \tag{3}$$

The electric field is affected by both positive and negative charge densities, which are associated with ion concentration via the elementary charge. Understanding this connection is essential for grasping the dynamics of the electric fielde_0.

$$p_e = e_0 p \tag{4}$$

$$n_e = e_0 n \tag{5}$$

In scholarly literature, the movement of charge species is frequently illustrated through the utilization of the Nernst-Planck equation.

$$\nabla . [-D\nabla p - b + p\nabla\varphi] + \vec{u}.\nabla p = R \tag{6}$$

$$\nabla . [-d\nabla n - v - n\nabla\varphi] + \vec{u}.\nabla n = R \tag{7}$$

Within this context, the positive (p) and negative (n) ionic concentrations are essential variables. To streamline simulation, it is assumed that the mobility of both positive and negative ions $(b+ = b- = b\,)$ remains constant. While the actual ionic mobility of the dielectric fluid may vary, the effect of charge mobility has not been explored. The derivation of the diffusion coefficient for charged particles is accomplished through the application of the Stokes-Einstein relation.

$$D = \frac{bk_bT}{e_0} \tag{8}$$

In the equation of Nernst-Plank, 'b' signifies ionic mobility, 'k-b' refers to Boltzmann's constant, and 'T' represents absolute temperature the concluding elements in these equations delineate the reaction rates that oversee the generation of three charge. Remarkably, this aspect retains uniformity in both equations 6 and 7, adhering to the established format commonly observed in academic discourse.

$$R = k_D n_{eq} - k_R np \tag{9}$$

The symbols (k_D) and (k_R) denote the dissociation and recombination rate constants are symbolized by 'k-d' and 'k-r', respectively, while 'n-eq' signifies the equilibrium charge concentration in the absence of a significant electric field. If there's no electric field, this term equals zero. The equilibrium rate constant can be articulated as per the conventional format often encountered in academic literature.

$$k_{D,0} = k_R = \frac{2be_0}{\varepsilon} \tag{10}$$

The expression for the enhanced dissociation rate constant is presented below, following the conventional format commonly employed in research papers.

$$k_D = F(\omega_e)k_{D,0} \tag{11}$$

The ONSAGER field enhancement function, derived from Onsager parameters it's a concept from statistical mechanics, used to describe the behavior of irreversible processes in systems far from equilibrium. is utilized to modify the dissociation rate constant. This association is described in accordance with the typical format commonly employed in research papers.

$$F(\omega_e) = \frac{I_1(4\omega_e)}{2\omega_e} \tag{12}$$

$$\omega_e = \sqrt{\frac{(e_0)^3|\vec{E}|}{16\pi\varepsilon^2 k^2{}_b T^2}} \tag{13}$$

In nonpolar fluids such as dielectric liquids, Langevin's analysis (equation 11) delineates the maximum value of the recombination rate. Integrating the enhanced dislocation rate, equation 9 can be revised as demonstrated below, adhering to the conventional structure found in research papers.

$$R = \frac{2be_0 n^2{}_{eq}}{\varepsilon}(F(\omega_e) - \frac{n_e}{n^2{}_{eq}}) \tag{14}$$

In the realm of electrostatics modeling, Poisson's equations are utilized, with the charge density being described as the difference between the charge densities of individual ionic species. This approach aligns with the typical structure commonly found in research papers.

$$\nabla.\vec{E} = -\nabla\varphi^2 = \frac{\rho e}{\varepsilon} = \frac{(p_e - n_e)}{\varepsilon} \tag{15}$$

In this context, φ is utilized to signify the applied potential, while ε is employed to denote the electrical permittivity of the fluid.

Electrokinetic: -

- Driven microfluidics involves various physics principles that utilize electric fields to manipulate fluids, primarily for pumping or mixing. The main electrokinetic phenomena include:
- Electroosmosis
- Electrophoresis
- Di electrophoresis

Numerical Frame work: -
Modeling: -

- COMSOL Multiphysics enables engineers and scientists to model and simulate interconnected physics phenomena across various domains, such as electromagnetics, heat transfer, fluid dynamics, and structural mechanics.
- Develop geometry in COMSOL optimized for fluid dynamics.
- Specify the maximum element size as 0.2 and the minimum as 0.00192.

- The fundamental equations governing the operation of an electrohydrodynamic (EHD) pump include the continuity equation, Navier-Stokes equation, Poisson-Boltzmann equation, Gauss's law, Poisson equation, and species charge transport equation. These equations are discretized for numerical analysis.
- Continuity equation: -

For incompressible flow the continuity equation is: -

$$\Delta . u = 0$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\frac{u_{i+1.j-u_{j-1.j}}}{2\Delta x} + \frac{v_{i.j+1-v_{i.j-1}}}{2\Delta y} = 0$$

- Navier-Stokes equation: -

For incompressible flow, the 2D Navier-Stokes equation are: -

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

- Momentum equation: -

The momentum equation for an incompressible, Newtonian fluid under the influence of an electric field is given by: -

X, Y- Momentum Equation

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + f_{e,x}$$

$$f_e = \rho_e E - \frac{1}{2}E^2 \nabla_{\in}$$

- Poisson-Boltzmann equation: -

The electrostatic potential in a fluid with free charges: -

$$\nabla^2 \emptyset = -\frac{\rho_e}{\epsilon}$$

- Gauss's Law equation: -

Gauss's law relates the electric field to the charge distributions

$$\nabla . E = \frac{\rho_e}{\epsilon}$$

$$d\emptyset_E = \overrightarrow{E}.d\vec{A} = E\ dA\ cos^{\theta},$$

$$d\emptyset_E = \frac{q}{4\pi\varepsilon_0}\frac{dA\ cos^{\theta}}{r^2}$$

$$d\emptyset_E = \frac{q}{4\pi\varepsilon_0}d\omega$$

$$\emptyset_E = \oint \vec{E}\,.d\vec{A} = \frac{q}{4\pi\varepsilon_0}\oint d\omega$$

$$\emptyset_E = \frac{q}{\varepsilon_0}$$

- Poisson equation: -

For the electrostatic potential: -

$$\nabla^2\emptyset = -\frac{\rho}{\in}$$

$$\frac{\emptyset_{i+1,j-2_{\emptyset i,j}+\,\emptyset_{i-1,j}}}{\Delta x^2} + \frac{\emptyset_{i,j+1} - 2_{\emptyset i,j} + \emptyset_{i,j-1}}{\Delta y^2} = -\frac{\rho i,j}{\epsilon}$$

- Species charge Transport equation: -

For ion transport in a fluid, the Nernst-plank equation is used: -

$$\frac{\partial c}{\partial t} + \nabla.(uc) = D\nabla^2 c - \nabla.(\mu c\nabla\emptyset)$$

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla.(\rho\vec{v}Y_i) = -\nabla.\vec{J}_i + R_i + S_i$$

We conducted an analysis of an electrohydrodynamic (EHD) pump using COMSOL 6.1 Multiphysics, where the following parameters were considered:

Name	Value	Unit
$Sigma\_w$	$0.11845[S/m]$	S/m
Eps_r	80.2	Unitless
$Zeta$	$-0.1[V]$	V
U_0	$0.1[mm/s]$	m/s
$Omega$	$50.265Hz$	Hz
D	$1e-11[m^2/s]$	m^2/s
c_0	$1[mol/m^3]$	mol/m^3

Geometry statistics : -

Description	Value
Number of Domains	2
Number of boundaries	18
Space dimension	2

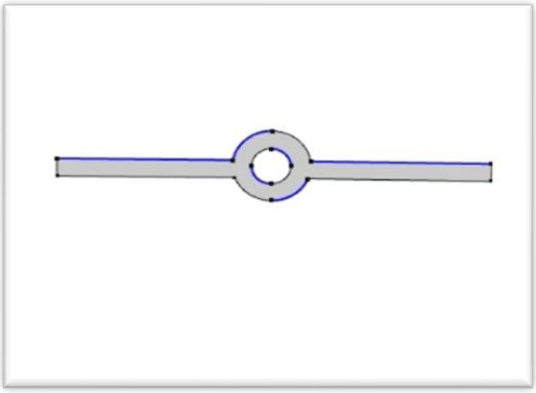

Fig.no.3: - Positive electric potential 1

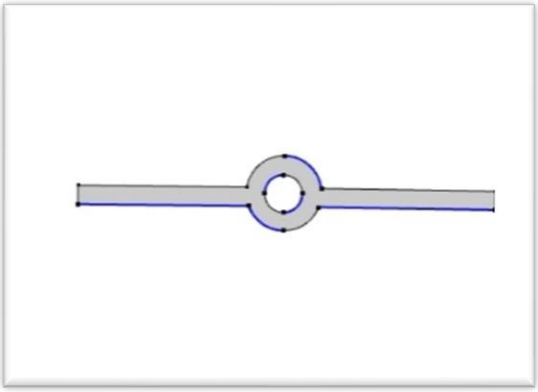

Fig.no.4: - Negative electric potential

Result and discussion: -

Case I -

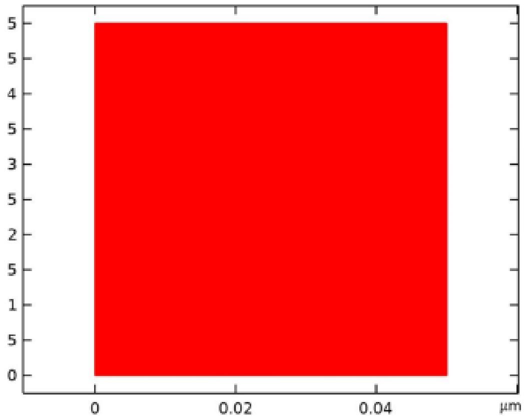

Fig.no.5: -Geometry

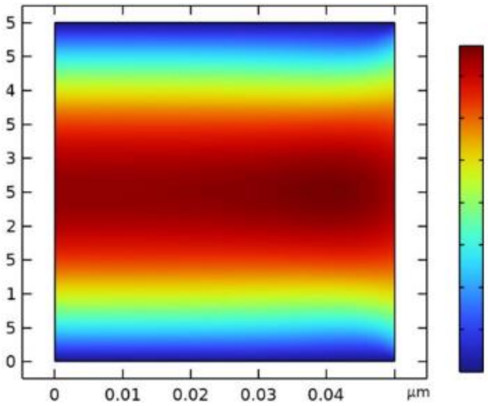

Fig.no.6: -Surface velocity magnitude

- Figure 5: The geometry has a width of 5µm and a length of 0.0499µm.
- Figure 6: This figure presents data on the surface velocity magnitude and demonstrates plug flow, which is utilized in the EHD pump.
- To conduct a simple pipe analysis, geometry was designed to showcase plug flow applicable in the EHD pump. Plug flow in an EHD pump refers to a flows profile where the fluid moves uniformly with the same velocity across the entire cross-section of the pipe.

Case II -

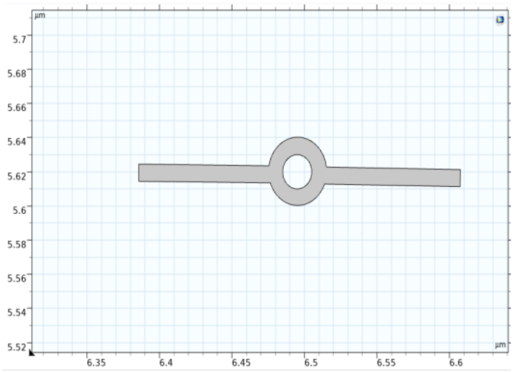

Fig. no.7:- Geometry

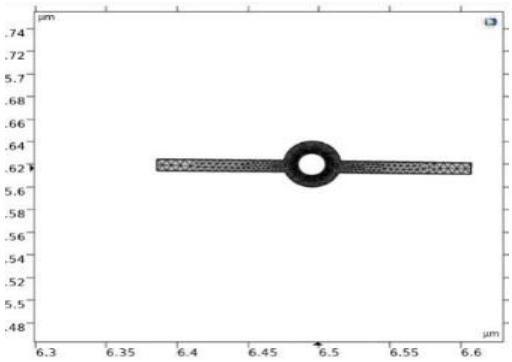

Fig.no.8: -Meshing

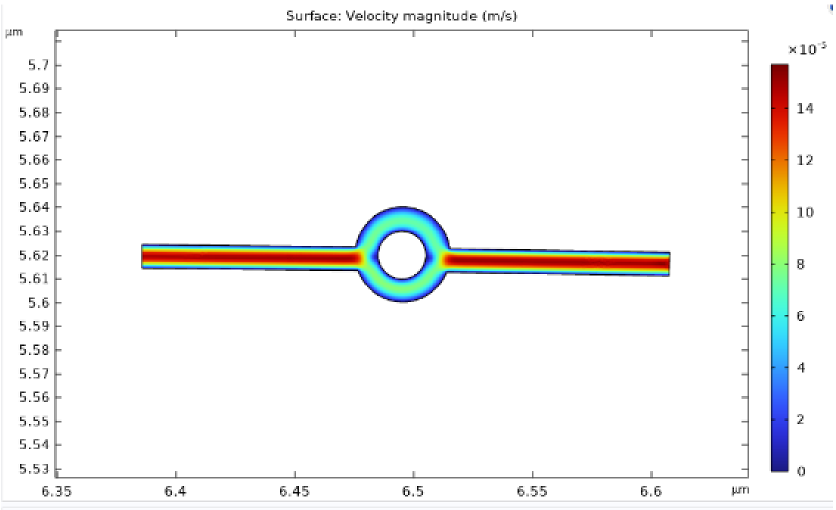

Fig. no.9:- Surface velocity magnitude

These figures depict our final designs used for our research. In these designs, we applied electrodes to induce fluid flow, resulting in the formation of a plug. Additionally, we included information about the velocity magnitude.

Meshing -

After the design phase was completed, the geometry was meshed, resulting in 1215 triangles and an equal number of elements. The mesh shows a minimum element quality of 0.5708 and an element area ratio of 0.0097665.

Description	Value
Status	Complete mesh
Triangles	1215
Number of elements	1215
Minimum element quality	0.5708
Element area ratio	0.0097665
Mesh area	0.002848[μm]

Conclusion: -

COMSOL Multiphysics is a commercial software that facilitates the modeling of multiphysics systems, integrating various physical phenomena including fluid dynamics, heat transfer, electromagnetics, and structural mechanics. It supports virtual prototyping and analysis of designs under diverse conditions. Electro-hydrodynamics (EHD) involves the study of the interaction between electric fields and electrically conductive or dielectric fluids, commonly used in pumps and fluid manipulation applications. EHD pumps are employed in wrist-mounted drug delivery systems to achieve precise fluid flow for localized medication administration. They are also utilized in wearable health monitoring devices for fluid-based sensing and diagnostics on the wrist. The velocity gradient in an EHD pump indicates the change in fluid velocity induced by the electric field, which is essential for comprehending pump performance. COMSOL facilitates visualization and analysis of this gradient, aiding in the optimization of pump design. EHD pumps offer several significant advantages, such as having no moving parts, enabling precise fluid control, operating silently, consuming low power, and being compact and lightweight. EHD flow is crucial for precise fluid manipulation, enhanced mixing and transport, and the elimination of moving parts. However, EHD flow faces limitations such as restricted flow rate and the complexity of design and optimization efforts.

References

[1] Langevin P. (1903). "Recombination et al. Mobilites des ions dans les gaz." Annals of Chemistry and Physics, 28(433), 122.

[2] Castellanos, A.& Perez, A. (2007). "EHD systems. "In Springer Handbook of Experimental Fluid Mechanics, Springer - Verlag.

[3] Gharraei, R, et al. (2001). "Experimental investigation of electro hydrodynamic conduction pumping of various liquid films using flush electrodes. "Journal of Electrostatics, 69(1), 43-53.

[4] PATEL, V.K, & SEYED YAGOOBI, J. (2014). "Recent experimental advances in electro hydrodynamic conduction pumping research, "In 2014 IEEE Industry Application Society Annual Menting, IEEE.

[5] NASSAR, M, et al. (2020). "Experimental models of the variation of HEE-7100 and HFE-7000 electric properties with temperature, "IEEE Transactions on Industry Applications, 56(4), 4193.

[6] O'Connor, N, & YAGOOBI, J. (2021). "An innovative EHD conduction pumping design for swirl flow generation. " In Proceedings of the 2021 IEEE. Piscataway, NJ, USA: IEE, pp. 1-6.

[7] Mao, Z, LIJUKA, T, & MAEDA, S. (2021). "Bidirectional electro hydrodynamic pump with high symmetrical performance and its application to tube actuator."Sensors and Actuators A: physical, 332, 113168.

[8] TALMOR, M, & SEYED- YAGOOBI, J. (2021). "Numerical study of microscale EHD conduction pumping: The effect of pump orientation and flow inertia on heterocharge layer morphology and flow distribution control. "Journal of Electrostatics, 111, 103548.

[9] MAZUMDAR, A. M. H. (2022). "Emitting electrodes effect on the enhancement of heat transfer by a two-stage electro hydrodynamic gas pump."IEEE Transactions on Industry Applications, 59, 441-449.